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Bench-Scale Predictions of Mattress and Upholstered Chair Fires: Similarities and Differences

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ABSTRACT: The life safety hazard issues associated with flaming fires of mattress and upholstered furniture are explored. It is shown that full-scale heat release rate (HRR) is the dominant variable which needs to be controlled. This can be determined directly by full-scale measurement. In many cases, full-scale tests are not convenient to conduct. Thus, it is desirable that bench-scale procedures be available which can be used to predict some of the important features of the full-scale test. Such procedures have been developed at NIST for upholstered furniture during several prior studies. In the present work, differences between the behavior of mattresses and of upholstered furniture are explored. Mattresses and upholstered chairs are soft goods which are constructed in a somewhat similar way: both use padding foams or battings, covered by upholstery fabric. There are differences in construction, however. Mattresses are flat, whereas upholstered chairs normally have seats, backs, and side arms. Also, an upholstered chair is constructed normally on a wood frame, whereas a mattress has no structural components, or else has steel innersprings. The quantitative knowledge of mattress behavior is still not as advanced as that for upholstered furniture. Nonetheless, based on a recent set of tests, the behavior of mattress fires can be quantified initially. Especially, data are now available to predict whether or not a particular mattress construction will lead to a propagating fire. Similarly as for upholstered furniture, such a limit value can be used to determine whether certain regulatory pass/fail criteria are met. The relationship obtained is incomplete, however, because the known roles of ignition source power level (that is, kilowatts output) and geometrical configuration are not yet quantified. Also, there is not yet a detailed explanation for differences between the observed relationships for mattresses and for upholstered chairs. Thus, future work will need to be done to address and further quantify these effects.

KEYWORDS: fire hazard, fire tests, heat release rate, mattresses, scaling relationships, spread of fire, upholstered furniture

In this study we will focus exclusively on the peak heat release rate (HRR) as being the prime variable characterizing the hazard of real fires. Thus, it is important that the answer to the question be known: Why is HRR the single most important variable for fire hazard? During the course of the National Institute of Standards and Technology (NIST) studies in upholstered furniture and mattresses, this tenet was adopted about a decade ago, yet to some observers it has seemed confusing. After all, fire death statistics in many cases show cause of death due to the inhalation of toxic gases. Should we not be focusing on a products' toxicity, then, instead?

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To examine this issue, we must consider that the acutal delivery of toxic gases to the victim can be separated into two factors:

$$(\text{toxic effect, per kilogram of material}) \times (\text{mass loss rate})$$

The first factor says how toxic is the burning product, per kilogram. The second factor tells us what is the kilogram per second mass loss rate of the burning product. The toxic effect is expressed as $1/LC_{50}$ where the LC_{50} denotes the lethal concentration that can be measured for each product by conducting a toxicity test. Bench-scale toxic potency tests typically show most products being clustered within a factor of three; almost all remaining products are within a factor of ten.

Factors of 3 for differences in toxicity of products must be taken in the context of possible differences in their mass loss rate. For flaming fires, mass loss rates can range over several orders of magnitude. This explains the concern with accurate determination of the mass loss rate behavior of the product.

At this point, we need to discuss the relationship between mass loss rate and heat release rate. Heat release rate and mass loss rate are related closely; however, heat release rate is considered normally to be of much greater importance. The reason is twofold: (1) Heat release rate is related directly to the production of untenable temperatures or heat fluxes in the environment of the fire. (2) Heat release rate is a driving force for further spread of fire. Mass loss rates, by contrast, are only indirectly related to these two aspects of hazard.

To illustrate more directly the importance of HRR in controlling the fire hazard, a recent study was conducted by NIST to illustrate numerically which factors are important in determining life safety, and which are secondary [*1*]. In that study, one example case examined was for an upholstered chair, where a single chair was burning in a room. The study simulated room fires with the computer model HAZARD I. Four scenarios were examined:

1. base case, single burning chair in room,
2. double heat release rate of chair,
3. double toxicity of materials, and
4. halve ignition delay of burning chair from 70 to 35 s.

Using the criteria for incapacitation and lethality as built into this model, the final results were summarized as follows:

Scenario	Time to death, s
Base case	>600
Double heat release rate	180
Double material toxicity	>600
Halve ignition delay	>600

Very similar results were seen also in a study where full-scale room fire tests, not just computer simulations, were conducted [*2*]. From such studies we can conclude that the HRR has the dominant effect on lethality in these fire scenarios, whereas changing the product's toxicity or its ignitability behavior has only a secondary effect. Further details on quantification of HRR in fires are provided in a recent textbook [*3*].

Studies of HRR for Propagating Upholstered Furniture Fires

HRR in upholstered furniture fires has been studied at NIST since 1982, which was the year that the first instrument available for quantifying HRR for full-scale products—the furniture calorimeter—was developed. Room fires with upholstered furniture had previously been studied (since 1975), but until instrumentation for measuring HRR was developed, it was not possible to quantify hazard in a sound, simple way. During the period 1982 to 1985 a large number of HRR studies were done on furniture, both at NIST and at other institutions. These studies were described in a Monograph published in 1985 [*4*]. We will summarize here the pertinent conclusions from that work, but, before we do, we have to examine the concept of propagating versus nonpropagating fires.

Some upholstered furniture items, once ignited, propagate and progressively burn until nearly all of the item is consumed. We call these *propagating* fires.

Some fires, when ignited with a given ignition source, burn in the vicinity of the source, but the majority of the specimen is not consumed and the fire goes out once the ignition source burns out (or is turned off, in the case of a gas burner). We call these *nonpropagating* fires.

(A few fires are difficult to classify since they burn very slowly, nearly die out, but eventually increase in burning, reach a peak, and then proceed to burn until near-total consumption.)

The studies up to 1985 focused solely on propagating fires. These are, obviously, the fires of greater hazard. A predictive method was established for these fires. In line with the general philosophy that as much as possible of fire testing should be done in bench-scale tests [*5*], a technique based on bench-scale testing was evolved. The bench-scale test method used is the Cone Calorimeter, ASTM E 1354 [*6*], ISO 5660 [*7*]. The predictive method was developed by conducting full-scale tests in the furniture calorimeter [*8*], then verifying with some additional tests in a fire test room [*9*].

Thus, for propagating fires the following equation was developed

$$\dot{q}_{fs} = 0.63\,\dot{q}''_{bs} \begin{bmatrix}\text{mass}\\ \text{factor}\end{bmatrix}\begin{bmatrix}\text{frame}\\ \text{factor}\end{bmatrix}\begin{bmatrix}\text{style}\\ \text{factor}\end{bmatrix} \qquad (1)$$

where $\dot{q}_{fs}$ is the full-scale peak HRR (kW); $\dot{q}''_{bs}$ is the bench-scale heat release rate (kW · m^{-2}). The mass factor = the total combustible specimen mass (kg), and the other variables are taken as:

$$\text{frame factor} = \begin{array}{l} 1.66 \text{ for noncombustible frames}\\ 0.18 \text{ for charring plastic frames}\\ 0.30 \text{ for wood frames}\\ 0.58 \text{ for melting plastic frames}\end{array}$$

and

$$\text{style factor} = \begin{array}{l} 1.0 \text{ for plain, primarily rectilinear construction}\\ 1.5 \text{ for ornate, convoluted shapes}\\ \text{with intermediate values for intermediate shapes}\end{array}$$

This correlation was tested successfully and verified over a range of 400 kW to over 3000 kW. Figure 1 shows the measured versus the predicted values using this correlation.

We note that the equation predicts the *peak* HRR, since this is the variable which is most crucial to determining the fire hazard. A technique was also developed for predicting the

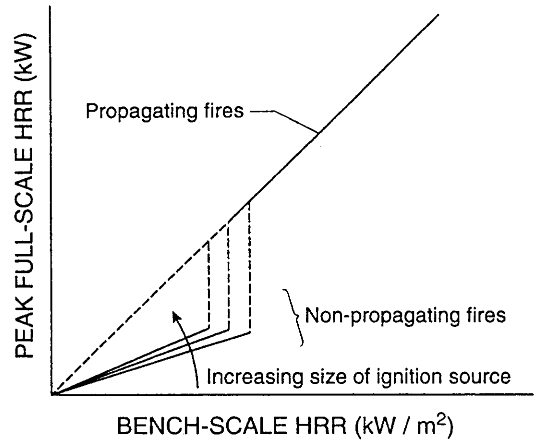

FIG. 1—*The relationship between predicted and measured peak HRR values for propagating upholstered furniture fires.*

shape of the HRR curve. The shape is primarily of importance in detailed fire modeling; the technique is documented in Ref *4*.

The bench-scale test conditions to be used, in addition to specifying the use of the Cone Calorimeter method, must also specify some test details. These were set at:

(*a*) irradiance = 25 kW · m^{-2},
(*b*) averaging period for $\dot{q}''_{bs}$ = 180 s after ignition,
(*c*) horizontal specimen orientation, with spark ignition, and
(*d*) in addition, details of specimen preparation also had to be specified.

The test irradiance and averaging period were not selected arbitrarily but, rather, were derived by doing exploratory studies with various irradiances and averaging periods, then selecting the conditions providing the best correlation to the full-scale results. The details of specimen preparation have also been published as a standard: NFPA 264A [*10*] and ASTM E 1474 [*11*].

Studies of HRR for Nonpropagating Upholstered Furniture Fires

The furniture tested in the earlier NIST studies encompassed primarily residential furniture specimens. Most of the specimens available for testing displayed "propagating" behavior. While some neoprene foam specimens were tested which did not propagate, enough data were not available to make predictions for nonpropagating fires.

An opportunity to study nonpropagating fires arose in 1988. For a number of years, the State of California had a standard test method (Technical Bulletin 133 [*12*]) for upholstered furniture. This test method involved subjecting upholstered chairs to a room fire test, with the specimen being ignited by a basket filled with flaming newspapers. Temperature, smoke, and other measurements were made, but HRR was not measured. A collaborative project between NIST and California's Bureau of Home Furnishings (BHF) was formulated in 1988 to quantify and improve the TB 133 method. This study entailed a number of tests using the furniture calorimeter, the Cone Calorimeter, and the California room fire test, and was completed in 1990 [*13*]. As a result of the study, TB 133 was revised and converted into a HRR test.

For the present purposes, it is important to note that the current California criteria require that the peak HRR be less than 80 kW. This value has been deemed to ensure life safety of occupants and also to be low enough so that the danger for igniting additional nearby combustibles is minimized. In general, chairs to pass the 80 kW limit can be built in two ways: (1) by limiting the amount of combustible upholstery material; or (2) by ensuring the HRR behavior of the upholstery system is good enough that a propagating fire cannot result. Chairs which pass by limiting only the amount of combustible mass are not typical *upholstered* chairs. Normally these would be stacking, secretarial, etc., chairs where only a very small amount of padding is used on a rigid chair construction.

Quantifying Nonpropagating Fires

The current, January 1991, edition of TB 133 does not yet provide a bench-scale alternative to full-scale testing. During the course of the NIST/BHF study, however, the technical groundwork for such an approach was developed successfully. First, we can consider the schematic presentation in Fig. 2. It can be seen that two different predictive correlations are needed, separate for propagating and nonpropagating fires. It is also important to determine the region in which the changeover occurs. Actual data for these relationships

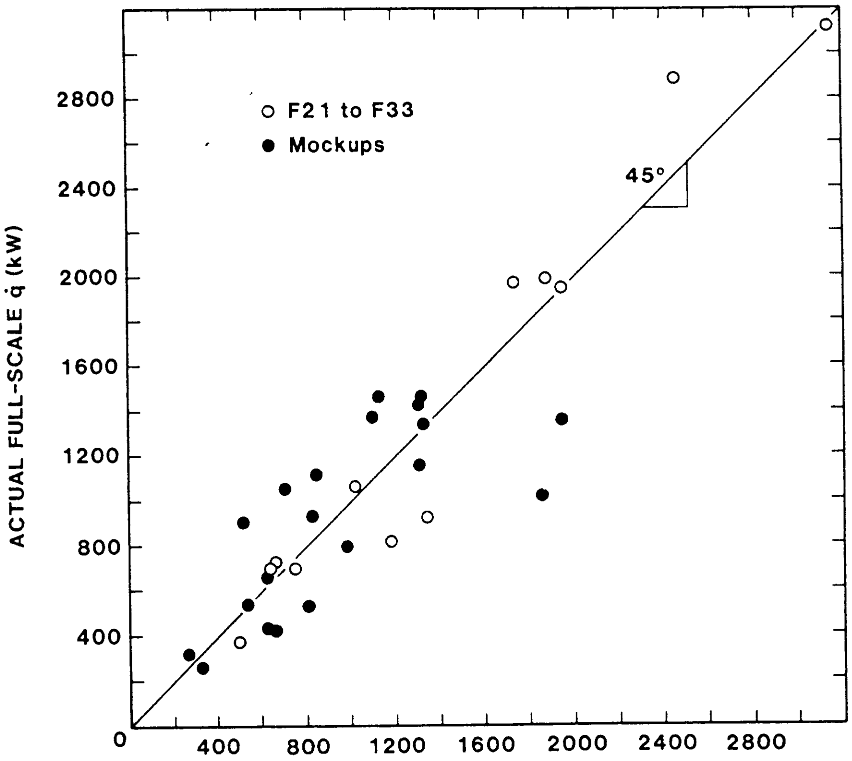

FIG. 2—*Schematic representation of regimes of fire propagation.*

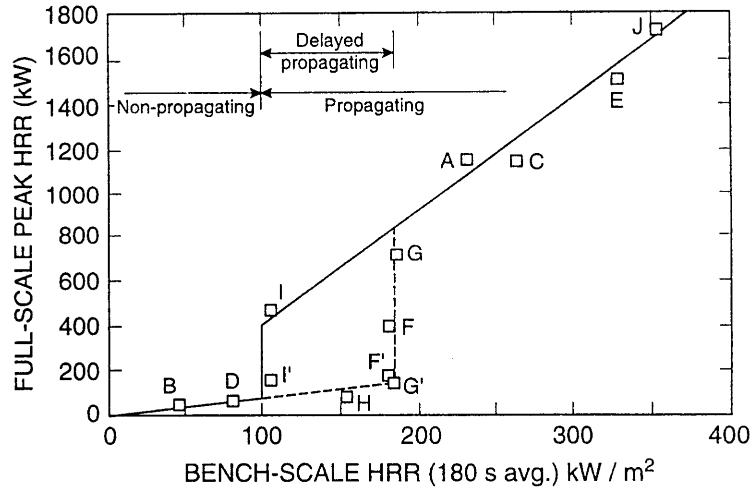

FIG. 3—*Results for upholstered chairs obtained during the course of the NIST/BHF study.*

were developed during the NIST/BHF study and are shown in Fig. 3. First, we can see that the following regimes are observed:

if $\dot{q}''_{bs} < 100$ kW/m² nonpropagating fire

if $\dot{q}''_{bs} > 180$ kW/m² propagating fire

For intermediate values, delayed propagation occurs. Specimens where both a primed and an unprimed letter (for example, I and I') are given in Fig. 3 exhibit such delayed propagation. The initial peak (corresponding mostly to fabric burning) is denoted with the primed letter, while the delayed peak (where the padding has gotten involved) is shown as unprimed. The experimental data of Fig. 3 provide substance to the schematic relationship indicated in Fig. 2. The data set available, however, was not very large; thus, future studies might indicate slightly different numerical boundaries for the regimes observed.

In this study, the Cone Calorimeter measurements were taken at an irradiance of 35 kW · m^{-2}. This was necessary since institutional furniture samples may not burn reliably at the lower 25 kW · m^{-2} irradiance.

Furthermore, for the fires in the propagating regime in Fig. 3, a correlation could be found as

$$\dot{q}_{fs} = 0.75\,\dot{q}''_{bs} \qquad (2)$$

This relationship does not express all of the general trends encompassed by Eq 1 since in this later study, mass, frame type, and chair style variables were not studied or reexamined independently.

The TB 133 limit of 80 kW for the full-scale test item corresponds to $\dot{q}''_{bs}$ = 107 kW · m^{-2}. To avoid implying an unwarranted precision, this number can be rounded as 100 kW · m^{-2}. Thus, we note that the 80 kW limit chosen by the BHF is rather finely tuned—it corresponds closely to the limit between fires which are nonpropagating (for example, D), versus those which are propagating (delayed-propagating), for example, I and I'.

Unlike the importance of a predictive relationship (such as Eq 1 or 2) in characterizing the propagating regime, a relationship predicting the actual HRR in the nonpropagating regime is not needed. This is because none of the nonpropagating fires create life safety hazards within the room of occurrence—these are fires which are intrinsically nonthreatening.

The Role of Specimen Mass and Other Full-Scale Features

It is important to recognize that the relationship for propagating fires needs a mass factor, a frame factor, and a style factor, while the relationship for predicting whether or not a propagating fire will occur needs none of those. We can focus especially on the role of specimen mass. For propagating fires, the peak full-scale heat release rate is directly proportional to specimen mass. This is because during peak burning nearly all of the chair is fire-involved. Thus, if the specimen mass is greater, there is more fuel being contributed. For the nonpropagating fire, by contrast, during peak burning only a small area is involved and it does *not* extend to all the edges of the specimen. Thus, knowledge of specimen mass is not needed in order to predict the full-scale results.

The Role of the Ignition Source

Some additional recent studies at NIST [*14*] have shown that, for a wide range of ignition source types and power output levels: (1) the HRR peak height is nearly independent of the ignition source used (we caution that this generality should not be expected to hold close to the boundary between propagating and nonpropagating/delayed propagation fires). (2) The type of ignition source used can affect drastically the time-to-peak.

Another NIST study, to be published in the near future, demonstrated that there is little change in the peak HRR when the *location* of an ignition source is varied; this, again, confirms earlier studies reported in Ref *4*. It must be emphasized, however, that both of the previously mentioned studies have dealt exclusively with furniture of relatively homogeneous construction. Much of commercial furniture is, in fact, highly nonhomogeneous and is likely to contain areas "sensitive" to ignition by a given source versus those less so.

Early NIST Studies on Mattress Flammability

Mattress flammability was first characterized at NIST more than a decade ago, prior to the availability of adequate means of measuring HRR in full-scale room fires. Subsequently, these data were reexamined and approximate HRR values were derived, based on some empirical relationships pertinent to the NIST burn room. The mattresses tested were mostly institutional (hospital, hotel, correctional, etc.), although a few domestic types were included. A bench-scale/full-scale correlation reporting these early studies was presented in the NIST monograph [*4*] and is shown in Fig. 4. The limit between nonpropagating and propagating fires is seen to be somewhere in the vicinity of 90 to 125 $kW \cdot m^{-2}$. For those initial tests, this was determined as a 180 s post-ignition average, given a test irradiance of 25 $kW \cdot m^{-2}$. The dotted trend line in Fig. 4 was intended only as a rough approximation to the actual data points; no specific predictive method was developed in conjunction with this initial mattress work.

Mattresses Studied by BHF and NIST

During 1990 to 1991, the opportunity arose for a joint NIST/BHF cooperative endeavor in further characterizing mattress HRR behavior. At BHF, the studies were funded by the

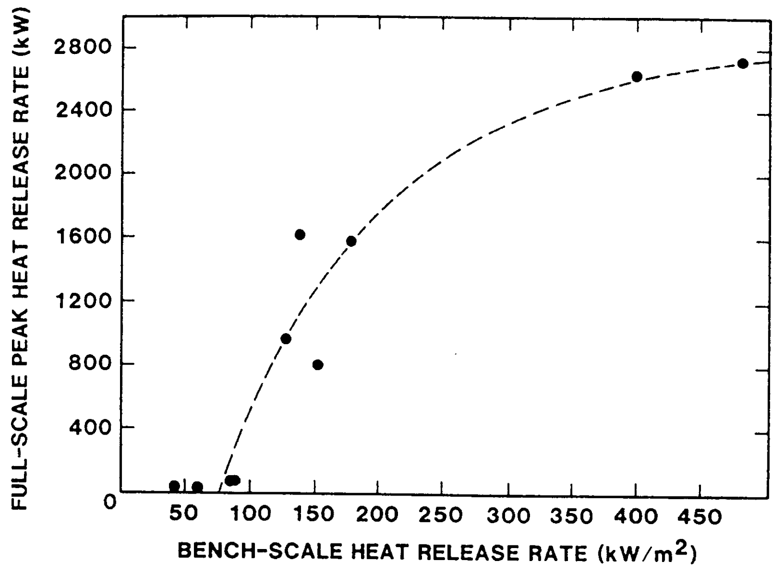

FIG. 4—*Early NIST correlation between bench-scale and full-scale mattress behavior.*

International Sleep Products Association (ISPA). At NIST work was conducted under funding from the Law Enforcement Standards Laboratory (LESL). ISPA provided a number of residential and institutional mattresses for testing, while for the LESL study prison and jail mattresses were procured. All full-scale testing was done at BHF, while all bench-scale testing was done at NIST.

Full-scale mattress testing by BHF was done in the same facility as used for TB 133 testing, and including the needed HRR instrumentation. The ignition source used was a T-head propane gas burner, supplied at the rate of 17 kW. The burner was the same as originally developed at the Fire Research Station in England [*15*]. All mattresses were tested as single, uncovered mattresses. In addition, certain selected specimens were tested with box springs and with several bedding combinations. Based on the results from the latter tests, it was concluded that box springs did not add to the hazard associated with the peak HRR measurement. With the ignition source used, it was also concluded that adequate fire involvement could be obtained without the use of bedding. The higher fuel load combinations of bedding used, however, could create a significant room fire hazard from the bedding alone. The full-scale test results obtained by BHF have been published already [*16*]. Based on these full-scale studies, BHF have also issued Technical Bulletin 129 [*17*]. The test criterion for HRR that California will be using is the same 80 kW as is used in TB 133 for upholstered furniture.

Most of the bench-scale Cone Calorimeter testing was conducted at NIST in the horizontal orientation at an irradiance of 35 kW/m^2, a small number of comparison tests were also done at 25 kW/m^2. Specimen preparation followed the prescriptions given in the NFPA 264A standard.

Results from Cone Calorimeter tests conducted at an irradiance of 35 $kW \cdot m^{-2}$ are compared against the full-scale test results in Fig. 5. The full-scale results plotted are only for those tests where BHF tested a single mattress, subjected to the T-head burner ignition source. The tests conducted using box springs and, likewise, those where the test mattress was covered with bedding, were not numerous enough to permit a similar comparison to

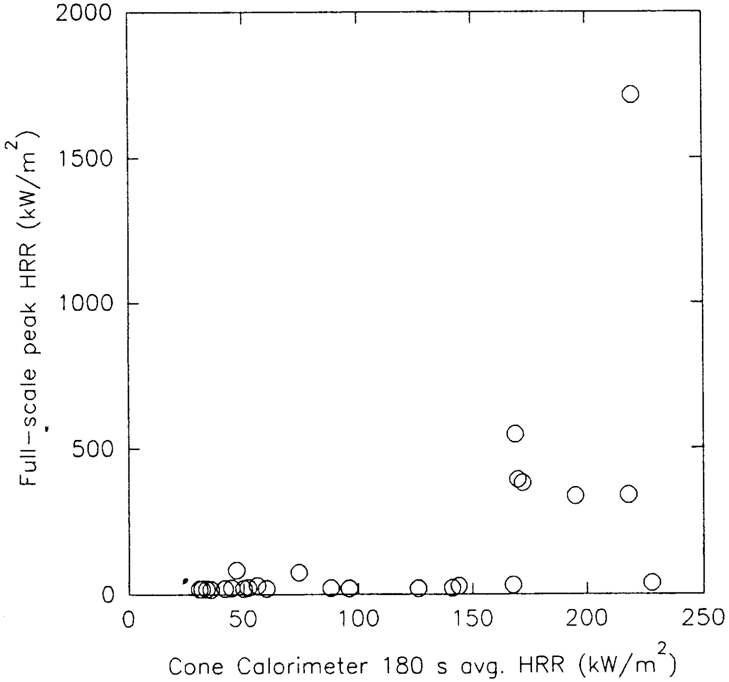

FIG. 5—*Mattresses—comparison of bench-scale (NIST data) and full-scale (BHF data) behavior.*

the bench-scale results. A simple correlation for the propagating-fire regime is not observed. This can be ascribed both to the relatively small number of propagating fires that were studied and to the effects of variables not examined. For instance, examination of the full-scale results from the BHF tests [*16*] will show effects of the presence or absence of mattress innersprings; enough data pairs are not available, however, to suitably quantify this effect.

It is possible, however, based on the experimental data to delineate the fire regimes. The results from this new work shows that propagating fires do not occur until a $\dot{q}''_{bs}$ value of around 140 to 170 kW · m^{-2} is reached. This contrasts to the range of 90 to 125 kW · m^{-2} seen from the early work. In addition to some measurement uncertainties of the early work, two other variables can be identified:

1. An irradiance of 25 kW · m^{-2} was used in the earlier work, compared to 35 kW · m^{-2} for the current studies.
2. The full-scale test mattresses in the earlier work were covered with a complete set of bedding, in contrast with the uncovered mattresses examined in the current work.

Both of these factors would suggest that the transition region would be at a higher level in the present work. The irradiance aspect can be explored directly, since data are available. Figure 6 shows this comparison. The correlation is only indicative since, while the 35 kW · m^{-2} points represent, in most cases, an average of three tests, the 25 kW · m^{-2} points are only single-value numbers. Also, it should be noted that points where the specimen did ignite in the 35 kW · m^{-2} tests but did not ignite in the 25 kW · m^{-2} tests are not plotted.

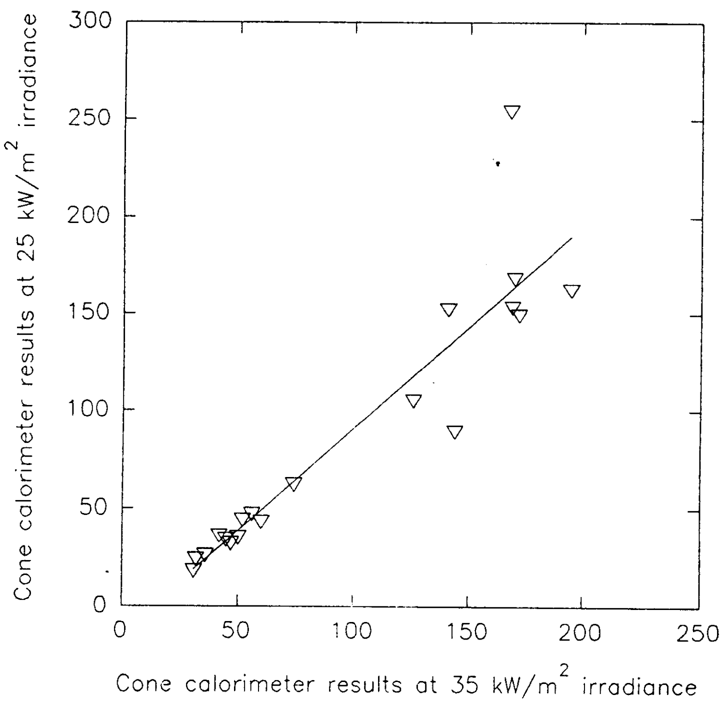

FIG. 6—*Comparison between Cone Calorimeter mattress results (180 s average values) at 35 and at 25 kW · m^{-2} irradiance.*

The correlation follows

$$\dot{q}''_{(25)} = 1.044 \cdot \dot{q}''_{(35)} - 13.5 \tag{3}$$

Thus, when a HRR of 100 kW · m^{-2} is attained using a 35 kW · m^{-2} irradiance, the corresponding HRR value using a 25 kW · m^{-2} irradiance would be 90.9 kW · m^{-2}. This explains about 10 of the 30% spread between the current results and the old ones. Part of the remaining difference then should be ascribed to the fact that mattresses which might be just on the nonpropagating side of the transition when tested without bedding may show propagation when tested with bedding.

Permanence of Fire-Retardant Formulations

Of special interest to the corrections community has been the issue of permanence of fire retardants in mattresses. A significant fraction of current-day correctional mattresses use boric acid treated cotton batting as the core material. This treatment is impermanent in that it is subject to both mechanical segregation and leaching. Thus, part of NIST activity involved developing a leaching procedure and subjecting all bench-scale specimens to Cone Calorimeter testing under two conditions: as-received, and leached.

No full-scale tests were conducted using leached specimens, since it was not practicable to develop a full-scale test procedure for this. For most specimens tested, leaching made absolutely no difference in HRR performance, as seen from the Cone Calorimeter tests

TABLE 1—*Results of leached specimens.*

No.	Core Material	180 s avg HRR, $kW \cdot m^{-2}$ As Received	Leached
1	normal PU	170	179
12	normal PU	194	196
13	PU/FR cotton batting	144	142
14	CAL 117 PU	162	165
18	CMHR (type A) PU	164	186
25	FR cotton batting	51	110
37	CMHR (type B) PU	31	33
38	CMHR (type C) PU	34	29
39	CMHR (type D) PU	126	172
40	Neoprene foam	32	30
41	polyester batting	141	139
42	FR cotton batting (used)	60	86
43	FR cotton batting (new)	57	113

(Table 1). The exceptions were two: (1) cotton batting treated with boric acid showed an increase in HRR by up to a factor of 2 when leached; (2) some polyurethane foam specimens showed HRR increases of up to about 1/3 when leached.

Even though the FR cotton batting mattresses roughly doubled their HRR when leached, none exceeded the value of 140 $kW \cdot m^{-2}$ after leaching. While the issue of boric acid impermanence may have implications for *cigarette* ignition resistance, the fact that the values do not increase sufficiently to go over to the propagating-fires regime suggests that this issue is not of relevance to *flaming* fire hazards.

The increase associated with leaching seen for polyurethane products is modest-to-nil. None of the FR-treated products with HRR values less than 100 $kW \cdot m^{-2}$ resulted in values greater than 140 $kW \cdot m^{-2}$ after leaching. Taking into account this slight possible worsening of performance when leached, a bench-scale HRR value of ≤ 100 $kW \cdot m^{-2}$ can be taken to represent the limit of the nonpropagating regime.

Discussion

The various research studies, conducted both at NIST and at BHF indicate that for both mattresses and upholstered furniture:

1. Bench-scale and full-scale HRR measurement techniques that are needed for quantifying the product behavior are nearly identical for both.
2. Propagating and nonpropagating regimes of flaming fire behavior are possible.
3. The nonpropagating regime results, in all cases, in fires which can be viewed as nonlife-threatening.
4. A bench-scale heat release rate value of *ca.* 100 $kW \cdot m^{-2}$ corresponds to the limit between propagating and nonpropagating regimes, provided that the measurement is obtained using a 35 $kW \cdot m^{-2}$ irradiance and a 180 s averaging period.
5. Impermanence of fire retardants can have a measurable effect in bench-scale testing, but these effects are relatively modest and can be compensated by appropriate choice of necessary limit criteria.

The differences include the following:

1. Quantitative estimates of peak HRR values in the propagating fire regime can be made for upholstered furniture, based on known construction details.
2. Prediction methods for quantifying the peak HRR of propagating mattress fires are not yet available; these, however, are all fires which are at least a moderate and, possibly, very serious life safety hazard.

Future Work

We have indicated in this study that limited quantitative guidance is already available for using bench-scale tests to distinguish between products which will lead to propagating full-scale fires and ones which will not. Yet, some issues still remain which can be explored appropriately.

1. In the case of residential occupancies, there may be an interest in quantitative characterization of products falling into the propagating regime. A predictive correlation for propagating mattress fires could be derived usefully; similarly, the correlation for upholstered furniture could be refined, especially in view of newer materials available today.
2. Smoke production was not discussed in the present study, since suitable full-scale mattress data were not available. This is an additional variable affecting life safety for which some only very preliminary upholstered furniture data have been available. A systematic study of smoke for both mattresses and upholstered furniture would be desirable.
3. Not enough is known about effects of ignition source location. This variable has not been explored for mattresses at all, and has been explored for upholstered furniture items where all portions are constructed in a similar manner. This effect needs to be studied for mattresses and for furniture of heterogeneous assembly.

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